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Flame-Powered Trigger Device for Activating Explosion Suppression Barrier

By R. A. Cortese and M. J. Sapko

UNITED STATES DEPARTMENT OF THE INTERIOR



BUREAU OF MINES



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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|--------------------------|---|-------------------------|--|
| A | ampere | mg/cm ² | milligram per square centimeter |
| atm | atmosphere, standard | mg/L | milligram per liter |
| cal/(cm ² ·s) | calorie per square centimeter per second | μm | micrometer |
| cm | centimeter | ms | millisecond |
| ft | foot | psi | pound (force) per square inch |
| ft ³ | cubic foot | psig | pound (force) per square inch, gauge |
| ft/s | foot per second | s | second |
| g | gram | V | volt |
| K | kelvin | W | watt |
| kW/m ² | kilowatt per square meter | W/(cm ³ ·sr) | watt per cubic centimeter per steradian |
| m ² | square meter | | |

FLAME-POWERED TRIGGER DEVICE FOR ACTIVATING EXPLOSION SUPPRESSION BARRIER

By R. A. Cortese¹ and M. J. Sapko²

ABSTRACT

The U.S. Bureau of Mines has developed a flame-radiation-powered trigger device to explosively activate suppression barriers to quench gas and coal dust explosions. The major component of the device is a silicon solar panel, which converts radiation from the developing explosion into electrical energy to initiate an electric detonator, which releases an extinguishing agent into the advancing flame front. Solar panels that are rated to produce 20 W of electrical power when exposed to the sunlight are producing about 200 W when exposed to a full-scale dust explosion.

The solar panel is electrically isolated from the detonator by a pressure-sensitive switch until the arrival of the precursor pressure pulse, which always precedes a deflagration. This combination of pressure arming and flame-powered photogenerator prevents false barrier activation and requires no external power supply.

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INTRODUCTION

The U.S. Bureau of Mines and countries other than the United States have been developing triggered barriers for suppressing incipient as well as fully developed gas and dust explosions in underground coal mines or other industries where combustible gases or dust can accumulate. In order for these barriers to be effective, it is important that incipient explosions be detected early and the barrier unit activated so as to contain the explosions. All triggered barriers consist of three essential elements: flame or explosion sensor, some type of a flame extinguisher dispensing system, and an effective extinguishing agent. Most trigger barriers have an optical or mechanical device to sense the developing explosion, an electronic signal-processing package to process the sensed signal and activate the dispenser, which rapidly disperses the extinguishing agent. The agent, which can be gas, liquid, powder, or some combination is discharged by some form of stored energy (explosive or gas pressure).

Until now, all rapidly activated triggering systems required an external power source to activate the triggered barrier. In most coal mines, it is difficult to provide power to those locations where explosion protection is needed. This report describes a novel light-powered device designed to trigger explosion-suppression barriers in underground coal mines, which is shown in figure 1. With a few modifications, this device can also be used for protection against dust explosions in grain-handling installations or in other industrial facilities for protection against dust and gas explosions.

Coal dust explosions are most often initiated by the electrical ignition of a pocket or layer of a flammable methane-air mixture that causes a local aerodynamic disturbance with sufficient violence to scour up, disperse, and ignite coal dust lying on the mine surfaces. If conditions are right, the resulting flame grows into a self-sustaining coal dust explosion and can propagate for long distances in the mine.



Figure 1.—Actual solar panel setup. Solar panel and pressure switch are mounted on rib inbye triggered barriers located on floor next to rib.

Triggered barriers are being used worldwide in potentially hazardous regions of the mine. A typical U.S. solar-panel installation is shown conceptually in figure 2. In such an installation, the sensor would be located in the proximity of the suspected explosion source and the extinguishment dispersal unit would be located sufficiently far from the sensor to provide time for the extinguishing agent to be discharged prior to flame arrival. It has been found that maximum effectiveness of the extinguishing agent is attained when it is ejected rapidly and early enough to blanket the entire mine entry cross section prior to flame arrival. If the extinguishing agent is dumped prematurely, the suppressant will be driven downstream and its concentration diluted by the explosion-induced wind before being overtaken by the flame. When the

trigger signal is late, the suppressant is dumped behind the flame where it has minimal effect.

Results of experiments conducted at the Bureau's Lake Lynn Laboratory (LLL) and Pittsburgh Research Center (PRC) indicate that during a self-sustaining dust explosion, a static pressure rise exceeding 0.1 atm always precedes the propagating flame. The time between the arrival of this pioneer wave and the flame that follows can range from a fraction of a second to greater than 1 s.

Figure 3 shows the pressure and flame histories associated with a coal dust explosion propagating in the single entry of the Bureau's LLL. This particular dust explosion resulted from the propagation of flame through a 400-ft zone dusted with a 65 pct (weight) rock dust-35 pct (weight) coal dust mixture equally distributed on

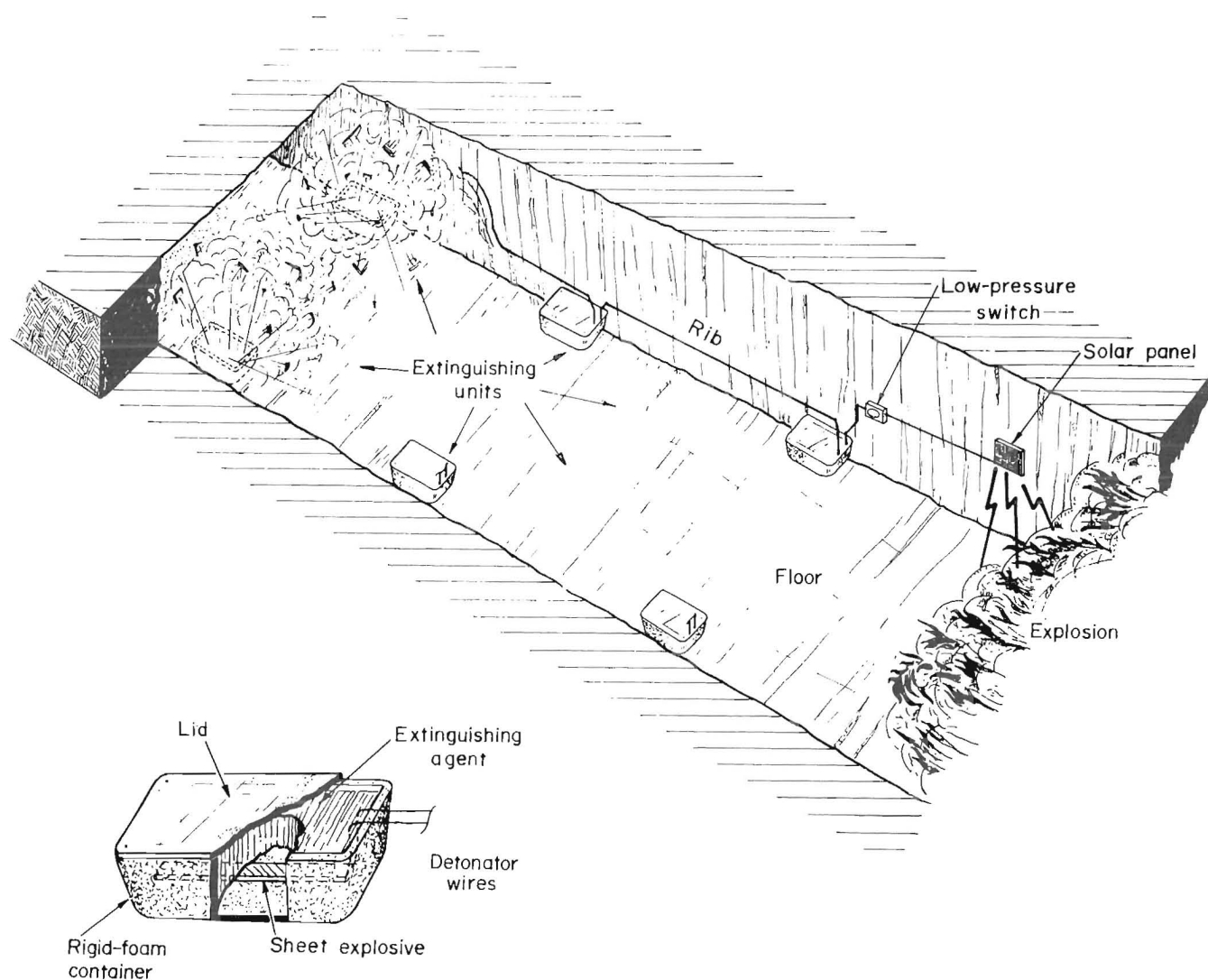


Figure 2.—Conceptual diagram of solar panel setup, with closeup of extinguishing unit.

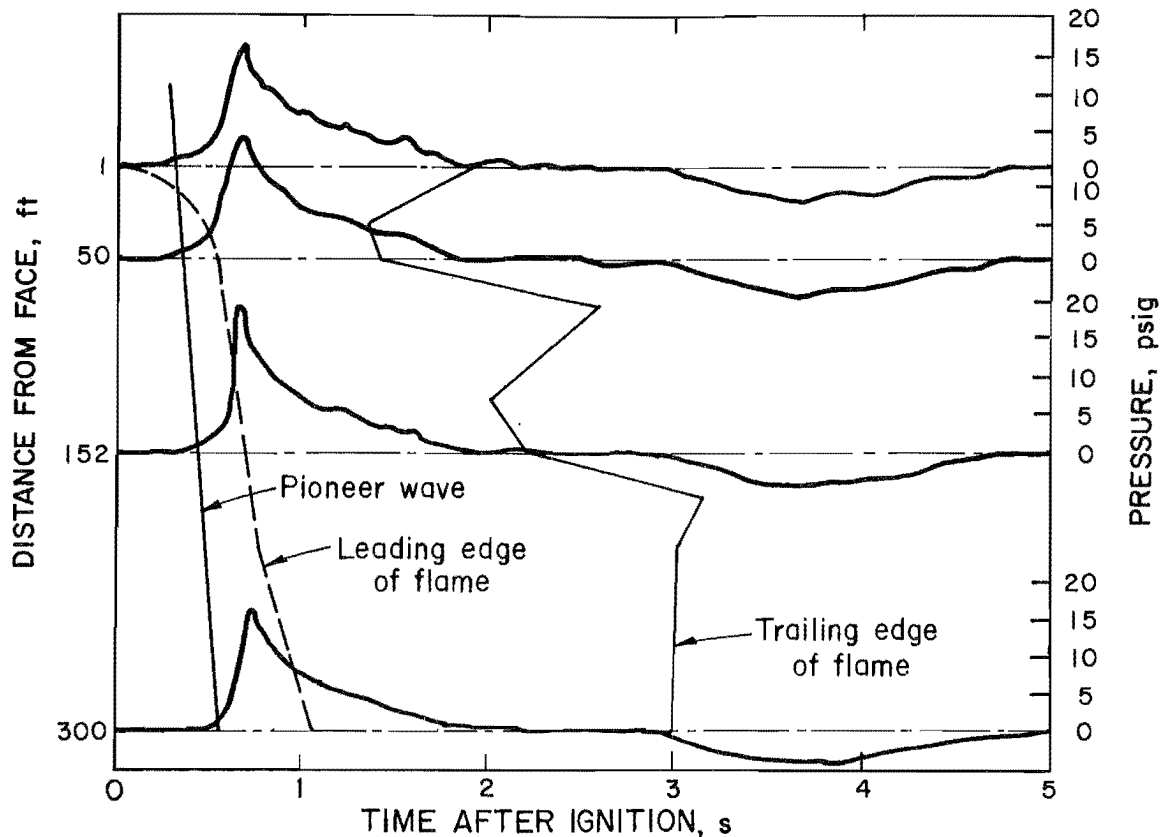


Figure 3.—Pressure and flame histories associated with coal dust flame in single entry of LLL.

roof shelves and the floor. This quantity of coal dust homogeneously dispersed in the entry results in a dust-air mixture containing 200 mg/L of dust. This dust explosion was initiated with a gas explosion propagating out of a 5,600-ft³ zone of 10 pct methane-air mixture juxtaposition to the dusted zone. The pioneer wave preceding the flame moves out toward the entry's open end, dispersing the coal dust-rock dust mixture. The pioneer wave activates the pressure switch, which removes a shunt from the detonator and connects it to the solar panel prior to flame arrival. The flame propagates through the dust cloud at an average speed of 750 ft/s, which is typical of a moderate strength explosion with the flame lagging about 0.5 s behind the pioneer wave at 300 ft from the closed end. About 10 ms after flame arrival, the electrical blasting caps detonate,

which in turn cause the rapid release of extinguishing agent into the advancing flame. The more violent dust explosions produce higher flame temperatures and therefore a shorter time separation between the pioneer wave and the flame. In a weak explosion, the flame may lag several seconds behind the pioneer wave, resulting in a longer time interval between pressure switch arming and flame arrival.

As part of its program to enhance worker safety in the mines, the Bureau developed an explosion-powered triggered barrier. The barrier should successfully quench the explosion before extensive damage results from a fully developed propagating flame front. To eliminate loss of power risk, the system was designed to require only the characteristics of an explosion for operation.

BACKGROUND

Current techniques for sensing flames or explosions for activating triggering barriers in mines include

1. Devices that sense directly the temperature rise of an explosion, such as a thermocouple. These devices are limited to sensing the flame at a single point in space and may trigger late when the flame front does not fill the entire entry cross section. To satisfactorily combat the poor response time, extremely fine thermocouple wires ($5\ \mu\text{m}$) must be used, which are fragile and easily damaged by shocks or impacts. The thermocouples also may be falsely triggered by incidental flames or heat sources from welding torches, etc.

2. Devices that detect ultraviolet, visible, infrared, or blackbody radiation emitted by the flame. These devices can be tripped by one or more false signals generated by miners' cap lamps, lights on vehicles or equipment for illumination, sparks, arcs, and hot surfaces.

3. Devices that respond to dynamic wind forces preceding the flame, such as wind vanes. These devices are slow to respond, sensitive to shocks and impacts, and can respond falsely to a roof fall or blasting. They can also fire prematurely during a dust explosion since there is little or no correlation between wind velocity and flame location.

4. Devices that fire in response to a static pressure rise. These devices have some of the same faults and

disadvantages as devices that respond to the wind, in that they can also respond falsely and prematurely.

The Bureau³ has developed a sensor-trigger device using a dual infrared flame sensor in combination with a pressure-arming unit. This combination is intended to prevent false and premature triggering. The pressure-sensing element switches on battery power to fire the detonator when the static pressure rises above 0.04 atm (0.5 psi), and each flame sensor views a separate narrow vertical field and must operate concurrently to turn on a firing relay.

The pressure switch energizes a relay that switches battery power to the dual infrared sensors. Each of the infrared flame sensors sights across the mine entry at a horizontal angle of 25° apart and through a vertically oriented slit. Each sensor must also detect radiation concurrently to energize the firing relay. This minimizes the possibility of false triggering by small radiation sources such as miners' cap lamps located some distance from the sensors.

This trigger device was tested in the Bureau's PRC experimental mine and found to operate satisfactorily during dust explosions. In the tests, the trigger device fired a detonator in a barrier to rupture a relief disk, releasing a quantity of water to suppress the explosion.

ACKNOWLEDGMENTS

The authors would like to acknowledge the valuable contributions made by Eugene Bazala and Jennings Lipscomb, physical science technicians, PRC, in the

implementation and testing of the explosion-powered trigger system.

EXPLOSION-POWERED TRIGGER THEORY

The explosion-powered trigger described in this report uses a more sensitive and faster acting pressure arming system than that described above.⁴ This feature allows suppression activities to take place closer to the ignition source where pressures are low and there is very little time separation between the pioneer wave and the arrival of flame at the barrier. This low-pressure condition occurs

in room-and-pillar and longwall operations where pressure relief takes place through crosscuts as the flame propagates into adjoining entries. Most importantly, the new system uses flame radiation to fire the detonators and does not require a battery or external power supply, making the system more maintenance free. Also, the new system can be used for both gas and dust explosions, whereas the earlier version required flame sensors with different spectral responses to ensure operation with gas explosions.

³Liebman, I., F. T. Duda, and R. S. Conti. Trigger Device for Explosion Barrier. U.S. Pat. 4,173,140, Nov. 6, 1979.

⁴Work cited in footnote 3.

Previous research at the Bureau has established that the temperature of a coal dust flame ranges from about 1,400 to 1,900 K and the flame radiant spectrum can be approximated by a blackbody continuum.⁵ Figure 4 shows the calculated blackbody spectral radiance of both a 1,400- and a 1,900-K source, corresponding to the minimum and maximum radiance from a coal dust flame, over the photon absorption region of silicon.

By integrating the blackbody continuum for a given temperature over wavelength for silicon's active region, the radiative input power to the solar panel is obtained. Then,

⁵Cashdollar, K. L., and M. Hertzberg. Infrared Temperatures of Coal Dust Explosions. *Combust. and Flame*, v. 51, 1983, pp. 23-25.

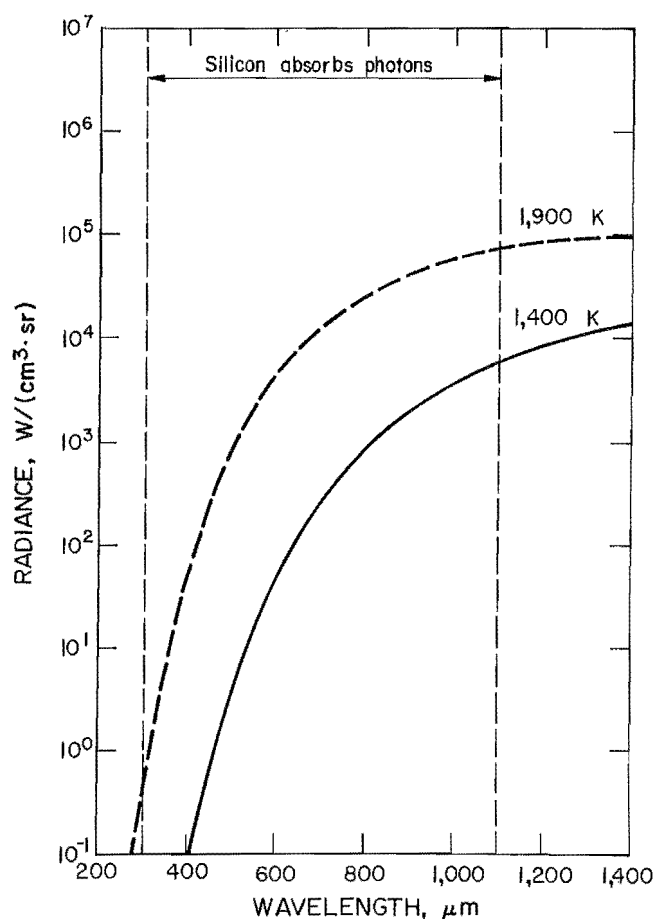


Figure 4.—Calculated blackbody radiation for 1,400- and 1,900-K flame, along with silicon photon absorption region (300 to 1,100 μm).

in order to predict the approximate solar panel conversion efficiency, the ratio of radiative input power to electrical output power must be computed. This ratio was obtained from the manufacturer's specification that under 1 sun, which is equivalent to 1 kW/m², a maximum of 20 W of electrical output can be produced. Since the solar panel's active region is approximately 0.146 m², this corresponds to 146 W (radiative), producing 20 W (electrical) for a power efficiency of 13.7 pct at the panel's maximum output, which is typical of current silicon technology.

To calculate the expected electrical output power of the panel in the presence of a flame, the fireball temperature of the dust explosion must be known. This temperature can be measured by a heat flux gauge located at the same location as the solar panel. The heat flux gauge used was a circular foil calorimeter manufactured by Thermogage Inc.⁶ with a response time of 30 ms for 98 pct of measured value. The gauges were calibrated with a blackbody cavity radiation source from 1,000 to 1,500 K. The temperature histories for the gas and dust explosions are computed from the heat flux gauge outputs using the following equation:

$$T = (HF \times K_c)^{0.25},$$

where T = calculated temperature, K,

HF = measured heat flux, cal/(cm²·s),

and K_c = conversion factor from cal/(cm²·s) to K⁴, $7.39 \cdot 10^{11}$.

Using this expression, the flame temperature profile was calculated for the dust flame passing the 150-ft measuring station (see figure 5, top). The figure shows that the calculated flame temperature peaks quickly, namely in 250 ms, which is within the response time of the gauge, to 1,750 K and decays rapidly behind the flame front because oxygen has been consumed and the combustion products loose heat to the cold mine surfaces. A similar pattern is found at the 50-ft station (see figure 5, bottom), where the gas flame peaks at 1,950 K.

Although gas flames, which generally have slightly higher temperatures (1,500 to 2,250 K) than dust flames,

⁶Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

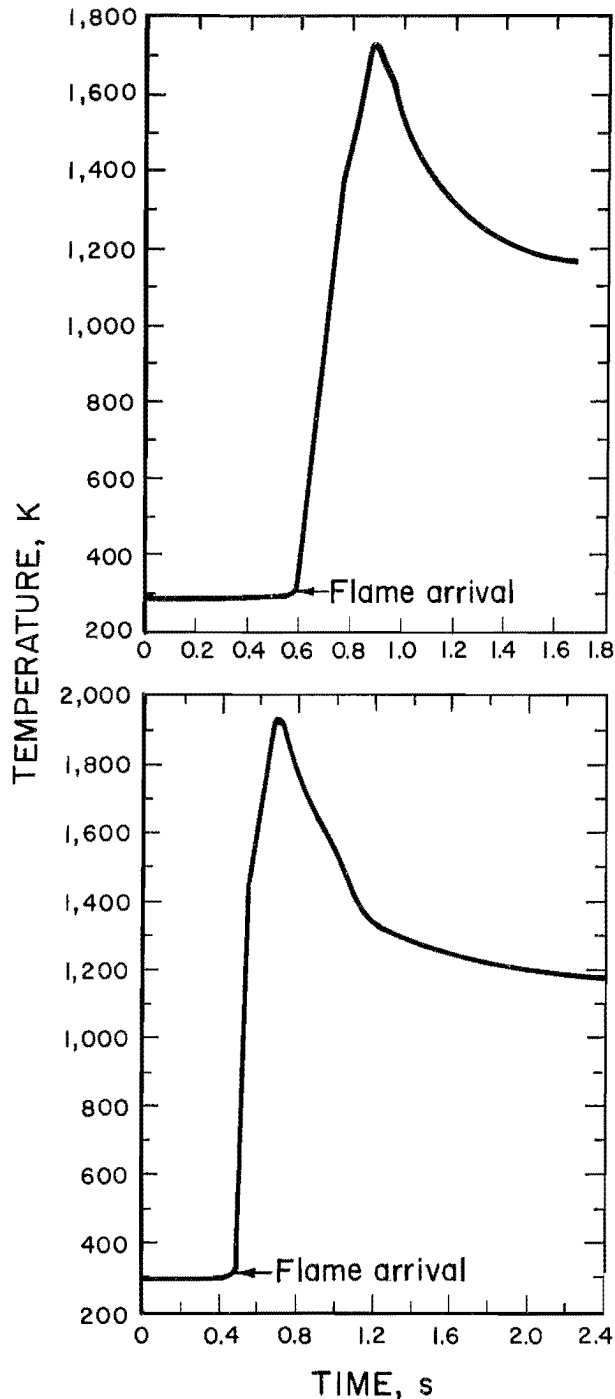


Figure 5.—Calculated temperature histories for coal dust (top) and gas (bottom) flames, based on heat flux gauge output.

are not as optically thick as dust flames, because the radiated energy is emitted in discrete water and carbon dioxide bands, the net radiative output power from gas explosions is still sufficient to fire a detonator with a solar panel. Furthermore, the presence of small amounts of a solid contaminant, such as dust particles, in the gas flame significantly enhances the radiative power output by increasing the optical thickness of the gas flame.

Figure 6 shows (1) the flame's total radiative power incident on the solar panel, assuming the flame engulfs the panel; (2) the net radiative power within the bandwidth of the silicon solar panel; and (3) the maximum electrical power output of the solar panel, all as functions of the flame temperature. The figure shows that even at the minimum flame temperature of 1,400 K, there is easily enough electrical power (10 W) to fire a 1-W detonator.

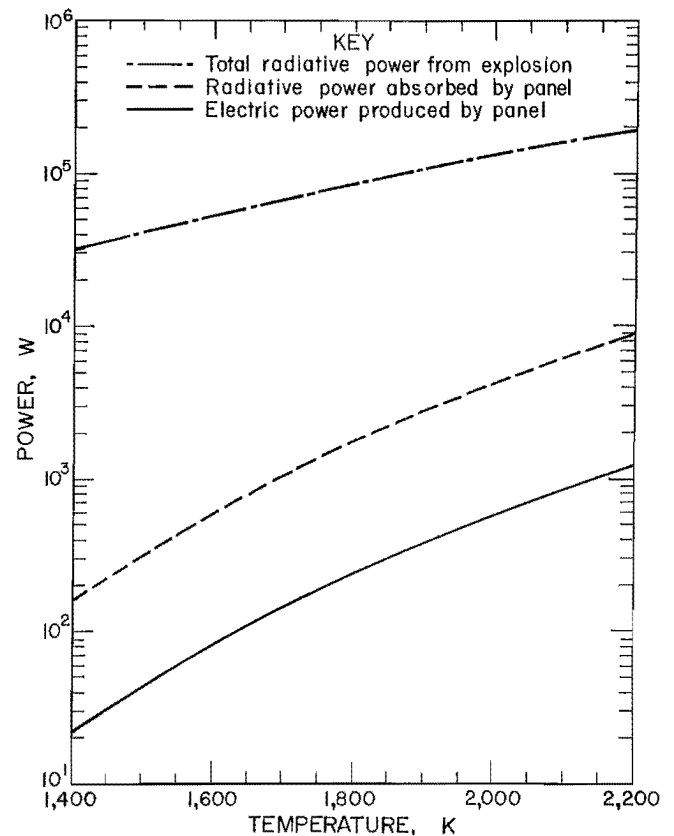


Figure 6.—Curves for total radiative power incident on solar panel assuming flame engulfs panel, net radiative power within bandwidth of silicon solar panel, and maximum electrical output of solar panel, as function of temperature.

SOLAR PANEL CHARACTERISTICS

The solar panel used was a Solec International, Inc., M-1136-3 Marine 20-W module. This panel measures 23.5 by 59.7 cm and consists of 36 silicon cells, each configured as a semicircle with a diameter of 10.16 cm.

A typical current-voltage characteristic curve⁷ of the solar panel is shown in figure 7. The figure shows that under a constant irradiance of 1 kW/m², the current output would approximately equal 1.32 A, the short-circuit current (I_{sc}), until the voltage reaches 16.5 V. Figure 7 also illustrates the optimum operating point for the solar panel for providing maximum electrical power output. This curve indicates that the current corresponding to the maximum efficiency occurs about 10 pct below the rated short-circuit current or 16.5 V.

Also shown in figure 7 is a typical load superimposed on the panel's characteristic curve.⁸ If multiple detonators are used, a parallel configuration must be used to ensure that all detonators are fired. The orientation of the load line is determined by the number of detonators connected in parallel and the internal resistance of each detonator.

Figure 8 illustrates the short-circuit current linear response to various level incident radiation.⁹ This is an important characteristic, since it shows that the resulting electrical power is directly proportional to incident radiation power. This is the premise on which the design is based.

RESULTS FROM EXPLOSION TESTING EXPLOSION-POWERED TRIGGER

Explosion tests were conducted in the D-Drift entry of the Bureau's LLL. Two solar panels were mounted on the ribs looking across the entry, one located 50 ft from the face and another at 157 ft from the face. Since the dusted zone starts at 40 ft and is scoured from the dusted surface

and carried outbye with the preceding pressure wave, the 50-ft panel saw a gas explosion. The 157-ft panel therefore saw a dust explosion. The heat flux gauges were situated a few feet inbye the panels at 47- and 152-ft locations.

⁷Turner, R. P. Solar Cells and Photo Cells. Howard Sams (Indianapolis, IN), 2d ed., 1980, p. 96.

⁸Work cited in footnote 7.

⁹Work cited in footnote 7.

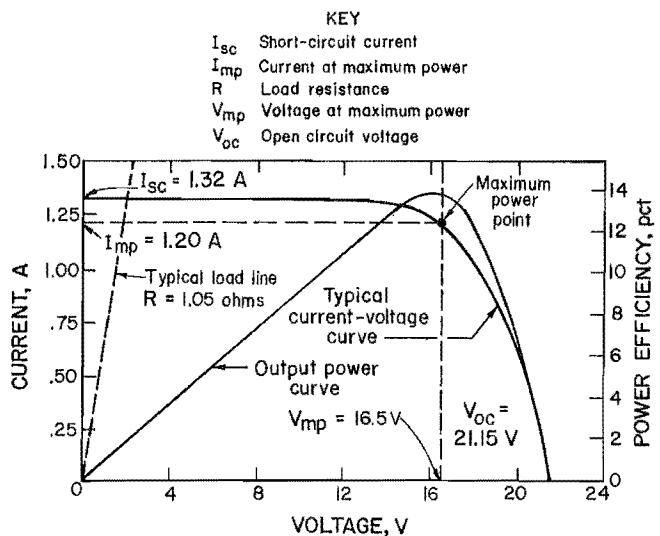


Figure 7.—Typical current-voltage characteristic curve of solar panel, along with output power curve, indicating maximum efficiency operating point. Also superimposed is typical detonator load line.

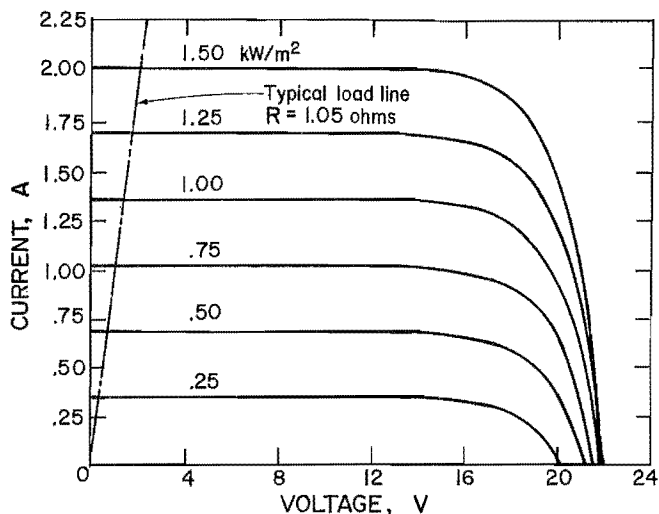


Figure 8.—Current-voltage curves of various levels of radiation. Illustrated is linear relationship between short-circuit current and incident radiation. (R denotes load resistance.)

Table 1 summarizes the results of the tests. Load power $P_{load} = (V)^2/1.05$. Maximum power (P_{max}) is obtained by multiplying P_{load} by the ratio of the panel efficiency at P_{load} and P_{max} (13.7 pct). This calculation assumes that the power efficiency at P_{max} is always 13.7 pct and always occurs at 16.5 V, independent of the radiant intensity.

Table 1.—Dust and gas explosion results from LLL

| Test | Calculated temperature, K | Heat flux, cal/(cm ² ·s) | Solar panel power | | |
|------|------------------------------|--|-------------------|--------------------------------|-------------------------------|
| | | | V | P _{load} ¹ | P _{max} ² |
| DUST | | | | | |
| 1 .. | 12.7 | 1,751 | 12.4 | 146 | 180 |
| 2 .. | 16.3 | 1,864 | 16.7 | 266 | 270 |
| 3 .. | 13.5 | 1,778 | 13.4 | 171 | 207 |
| 4 .. | 13.7 | 1,785 | 13.6 | 176 | 212 |
| GAS | | | | | |
| 1 .. | 19.5 | 1,948 | 14.0 | 187 | 206 |
| 2 .. | 20.4 | 1,972 | 13.0 | 161 | 190 |
| 3 .. | 26.5 | 2,105 | 14.4 | 197 | 212 |
| 4 .. | 26.2 | 2,099 | 8.3 | 66 | 121 |
| 5 .. | 26.0 | 2,095 | 4.7 | 21 | 66 |

¹Corresponds to the electrical power delivered to a panel load of 1.05 ohms.

²Maximum power that the panel would deliver under the given radiance.

Figure 9 shows P_{max} values compared with the theoretical curve. This figure shows that the measured dust explosion values compare favorably with theory.

On the other hand, as expected, the gas explosion data points lie considerably below the theoretical curve. Also evident in the results is the effect of only a small amount of fine coal added to the gas-air mixture prior to ignition. Two explosions of approximately the same temperature (2,100 K), one without coal dust (65 W) and one with 110 g of fine coal dust predispersed in the gas zone, resulted in a difference of a factor of 3 in output power.

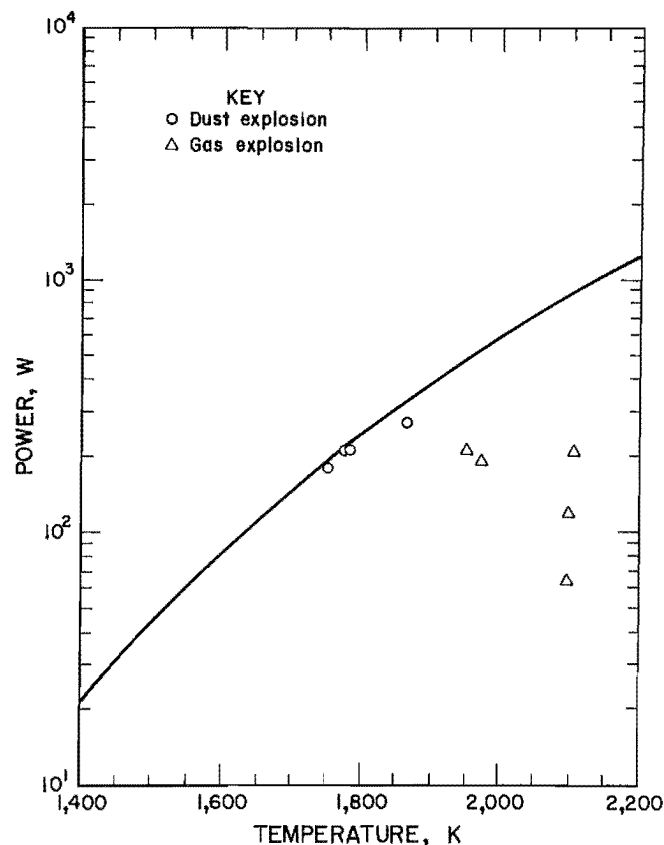


Figure 9.—Comparison between theoretical electrical output and dust and gas explosion results. Theoretical electrical output of panel is indicated by solid line.

It is evident from both sets of data that sufficient power is generated by the panel to fire a 1-W detonator, since the minimum electrical power obtained was 21 W.

WINDOW COATING

In view of the dustiness of underground coal mines, there has been some concern that the solar panel might get coated with sufficient dust to obstruct the flame

radiation from reaching the solar cells. Conducting the coating tests involves measuring the solar panel's output voltage when irradiated with a high-intensity incandescent

lamp with various amounts of dust sprinkled over the surface of the solar panel. Results shown in figure 10 indicate that a coal dust loading of 5 mg/cm² is required to reduce the output from a typical 100-W explosion below the 1 W necessary to fire the detonator. Rock dust, being translucent, does not obstruct the radiated light as effectively as opaque coal dust. Thus, figure 10 shows that five times as much rock dust as coal dust must be accumulated before the output is reduced below 1 W. These experimental dust loadings were the worst case, with a horizontal collection surface. Typical mine installations would either be on a rib or on the mine roof. In both the vertical and upside down orientations, the attracted, or adhering, dust was less than 1 mg/cm², indicating minimal reduction in output power. The solar panel was also covered with oil and water, and both of these substances slightly magnified the output of the panel, with oil having the greater effect.

Reduction of the light sensor sensitivity due to contaminant coatings on the sensor window was also examined during explosion tests. With the window mounted on the vertical and coated with coal dust or rock dust, the wind forces preceding the flame cleansed the window, such that there was no measurable difference in output power with or without the coatings.

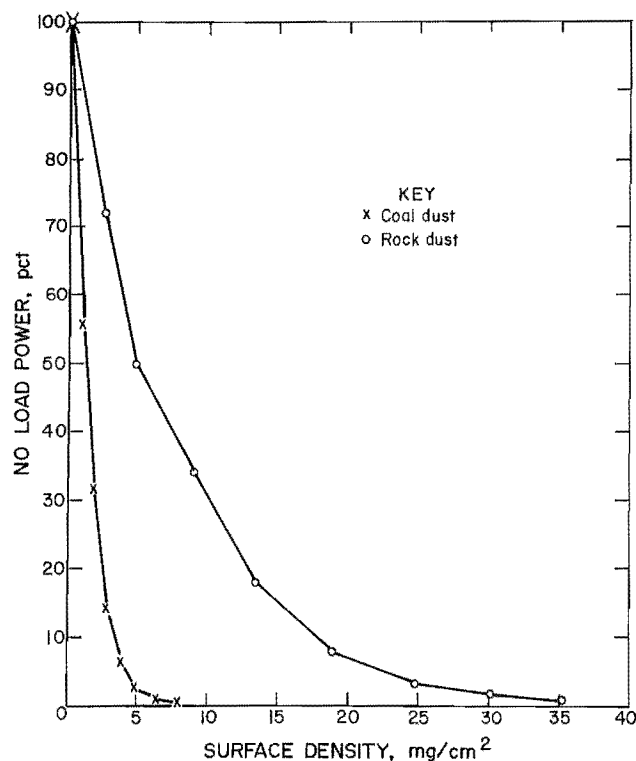


Figure 10.—Results from window-coating tests.

CONCLUSIONS

The Bureau developed solar cell-powered trigger barriers to quench gas and dust explosions in the early stages of development. The basic idea takes advantage of some of the destructive properties of dust explosion, namely the flame radiation and accompanying pressure rise, to stop the very explosion that is producing them. Solar panels that are rated to produce 20 W of electrical power when exposed to the sunlight are producing about 200 W when exposed to radiation emitted by a dust

explosion flame propagating in the Bureau's LLL. Owing to silicon's limited spectral bandwidth and its 13.7 pct conversion efficiency, this 200 W is only a small fraction of the 80,000 W of radiation striking the panel, but more than 100 times the power necessary to trigger the barrier. The electrical output power of the solar panel is present for a period of 0.25 to 1.0 s ahead of the flame, providing plenty of time to activate an explosively triggered barrier.